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13. ABSTRACT (Maximum 200 words)

ARO Grant DAAH04-95-1-0325 (P-33936-PH) has supported a research program to explore and implement concepts which utilize microwave magnetic envelope solitons in thin magnetic film device configurations for signal processing at microwave and millimeter wave frequencies. The work has produced various versions of a soliton oscillator, a soliton switch, and a soliton parametric amplifier. The work has also spawned a number of new device concepts, including an active delay line, several versions of a bistable oscillator, a decay free soliton train generator, and a mode locked spontaneous soliton generator. The switch concept has evolved into a simple phase sensitive on/off switch and a multi-port switch based on the self focusing properties of beam solitons. The original parametric amplifier idea, with the soliton transducer structure inside a microwave cavity, has evolved into a microstrip resonator device with localized parametric pumping and gains in excess of 29 dB. This represents a major breakthrough for magnetic film microwave devices. Work has also proceeded on the study of soliton formation, propagation, reflection, and interaction. A second major breakthrough has been achieved in the direct detection of microwave solitons in magnetic films by Brillouin light scattering.

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Microwave Magnetic Thin Film Soliton Device Physics

FINAL PROGRESS REPORT
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RESEARCH RESULTS

A. Problem Statement and Overview

ARO Grant DAAH04-95-1-0325 has supported research program to explore and implement concepts which utilize microwave magnetic envelope solitons in thin magnetic film device configurations for signal processing at microwave and millimeter wave frequencies. This program resulted in the first experimental work in the USA on high frequency envelope soliton devices based on magnetic thin films and positioned the CSU group as a key player in this emerging field. The initial objectives were: (1) the basic soliton device physics at 5 GHz of a microwave magnetic envelope (MME) soliton oscillator, an MME soliton switch, and a beam soliton deflector, (2) parametric soliton amplification, (3) soliton generation at 10 and 20 GHz, and (4) an internally pumped beam soliton cavity resonator.

The program has produced various versions of a soliton oscillator, a soliton switch, and a soliton parametric amplifier. The work has also spawned a number of new device concepts, including an active delay line, several versions of a bistable oscillator, a decay free soliton train generator, and a mode locked spontaneous soliton generator. The switch concept has evolved into a simple phase sensitive on/off switch and a multi-port switch based on the self focusing properties of beam solitons. The original parametric amplifier idea, with the soliton transducer structure inside a microwave cavity, has evolved into a microstrip resonator device with localized parametric pumping and gains in excess of 22 dB. This represents a major breakthrough for magnetic film microwave devices. Work has also proceeded on the study of soliton formation, propagation, reflection, and interaction. A second major breakthrough has been achieved in the direct detection of microwave solitons in magnetic films by Brillouin light scattering.

B. Summary of Results

The previous ARO program resulted in the first experimental work in the USA on high frequency envelope solitons in magnetic thin films and positioned the CSU group as a key player in this emerging field. The current program has yielded further results on device physics and the related propagation properties of MME solitons. Selected aspects of the work are reviewed below. Details may be found in the references listed in Section C. Except where noted, carrier frequencies were in the 5 GHz range. The review is intended to provide a reasonably self-contained summary description of the program accomplishments. An edited version of this section was also included in the funded renewal proposal for DAAG55-98-1-0430.

1. Soliton Basics

Figure 1 shows the microstrip delay line structure which is the basis of the MME soliton experiment. Diagram (a) shows the layout of the yttrium iron garnet (YIG) on gadolinium gallium garnet (GGG) film strip on the input-output antenna structure. Diagram (b) shows the input-output antenna and film setup in more detail. The output antenna is movable, so that the propagation distance can be easily varied. This setup is critical to the device and propagation experiments to be considered shortly.

The nomenclature in Fig. 1 is self explanatory. A microwave pulse applied to the input produces an MME pulse or soliton in the YIG film which propagates down the YIG strip and is detected at the output antenna. The overall nonlinear response is controlled by the input pulse

width and the input power. The propagation velocity or MME pulse group velocity v_g is controlled by the film-field geometry, the size of the static field, and the signal carrier frequency. For the case shown, with the static magnetic field **H** parallel to the propagation direction and antiparallel to the MME pulse carrier wave vector **k**, one has magnetostatic backward volume waves (MSBVW). The fundamentals of the magnetostatic wave (MSW) excitations which are excited in these experiments and may be used to create MME solitons are reviewed by Xia *et al.* (1997).

Figure 2 shows a schematic of the laboratory set-up which has been used for the soliton experiments. The YIG film between the poles of the electromagnet is the key element for the experiment. Figure 3 shows some representative input and output pulse data. As the input pulse is made wider, one forms MME solitons which are detected at the output antenna. The output traces shown in (c) and (d) correspond to higher order solitons. Besides multiple peaks, these higher order solitons have unique properties which may be exploited for microwave signal processing applications.

Xia *et al.* (1997) and Nash *et al.* (1998) have reviewed the basic properties of MME solitons. The key properties are (1) nonlinear wave packets which do not spread in width as they propagate, (2) a decay in amplitude which is typically twice as rapid as for linear MME pulses, (3) a phase profile which is constant across the pulse, (4) velocity characteristics which reflect the soliton order, and (5) self focusing properties. The first property is the one which makes MME solitons attractive for microwave device applications. Just as optical solitons may be used for robust optical fiber communications, MME solitons may be used for microwave delay and signal processing. The advantage here is frequency agility and time delay agility due to the electronic tunability of the MSW signals.

The rapid decay, on the other hand, presents a significant problem for MME

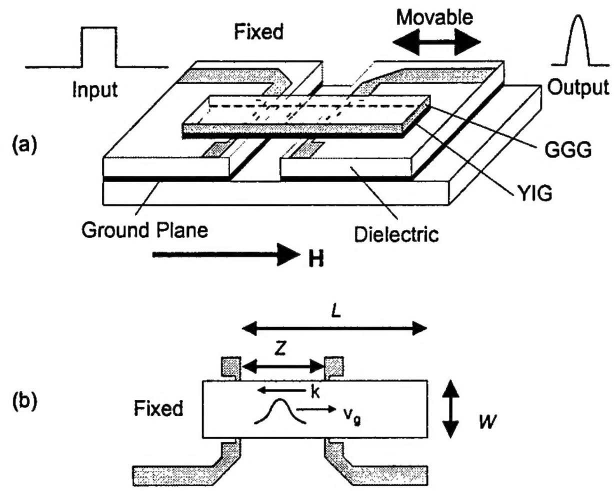

Fig. 1. Variable spacing transducer structure for MME soliton pulse measurements (Xia *et al.*, 1997).

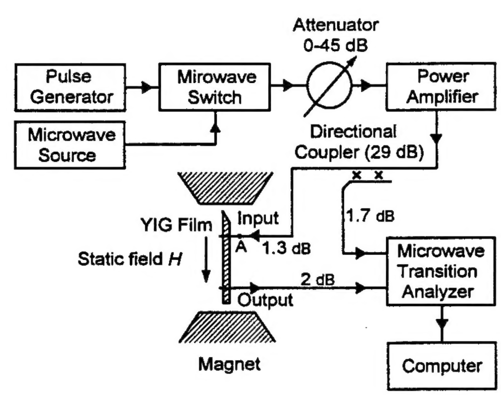

Fig. 2. Schematic diagram of MME soliton measurement instrumentation (Xia *et al.*, 1997).

soliton applications. Typical decay times are in the 100-200 ns range, the same as the desired delay times for the radar signal processing devices which may utilize these effects. As will be demonstrated shortly, parametric amplification through a third transducer element can be used to eliminate this problem. In addition, feedback techniques can be used to produce decay free soliton pulse trains for practical long time electronically tunable delay.

The phase, velocity, and self-focusing properties can be used to select out different types of solitons and to direct soliton pulses toward specific receiving elements. Such properties can be used to do phase and frequency selective switching and microwave logic. The ramifications of these effects are to be explored in the renewal program.

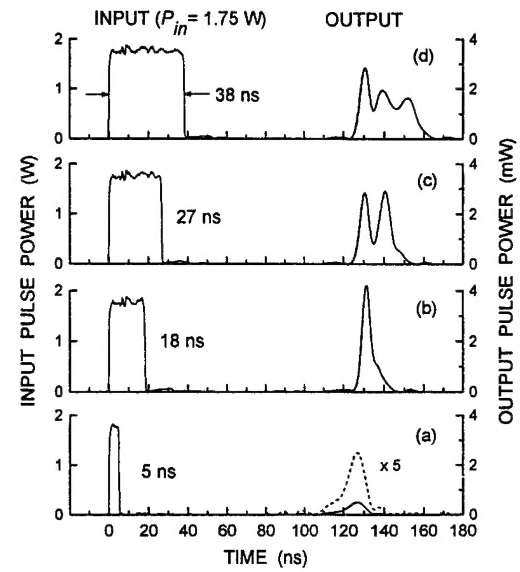

Fig. 3. Example of single and multi-soliton formation for 5 GHz magnetostatic backward volume wave pulses.

A large amount of work on the fundamental physics and device physics of MME soliton in YIG films has been accomplished under the current program. The key results include:

1. Characterization of "bright" and "dark" magnetostatic backward volume wave (MSBVW) and magnetostatic forward volume wave (MSFVW) solitons in YIG films.
2. Measurements of soliton amplitude and energy decay, and correlation with nonlinear theory.
3. Measurements of the dynamic magnetization response associated with MME solitons.
4. Measurements of the formation, propagation, reflection, and collision of MME solitons, and correlation of the soliton amplitude change with pulse width with nonlinear theory.
5. Measurement of the characteristic phase profiles associated with MME solitons, coupled with a new understanding of the role of signal phase in soliton formation.
6. Successful modeling of soliton profiles, power response, and formation times, based on the one dimensional nonlinear Schrödinger equation.
7. Measurement of the characteristic phase profiles associated with MME solitons, coupled with a new understanding of the role of signal phase in soliton formation.
8. Use of feedback to reduce soliton pulse decay, produce decay free MME soliton trains for extended times, and produce spontaneously generated mode locked solitons.
9. Use of parametric pumping to produce soliton pulse amplification.
10. Detection of Brillouin light scattering on MME solitons.
11. New MSW device concepts for switching and bistability.

Figure 4 shows two series of MME pulses at (a) low power and (b) in the soliton regime as a function of propagation time. The rapid pulse decay times on the order of 100 ns are clearly evident. It was found (Xia *et al.*, 1997) that while the amplitude decay rate increased for soliton pulses, the energy decay remains constant and directly related to the intrinsic decay rate for the YIG film. Further work to be considered shortly yielded ways to parametrically pump the pulses shown in Fig. 4 to produce real gain rather than the decay which is so conspicuous in the figure.

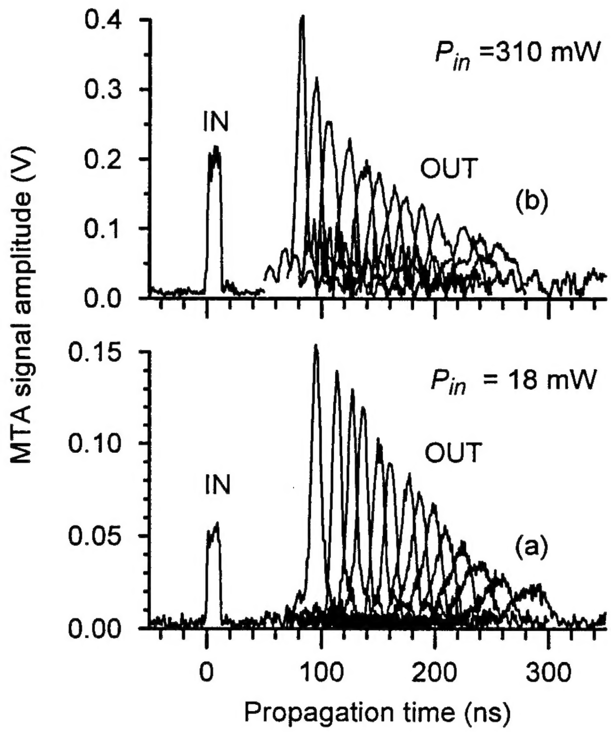

Fig. 4. Low power (a) and soliton (b) pulse decay vs. time. The carrier frequency was 5 GHz and the transducer separations were changed from 3 to 10 mm to obtain the data (Xia *et al.*, 1997).

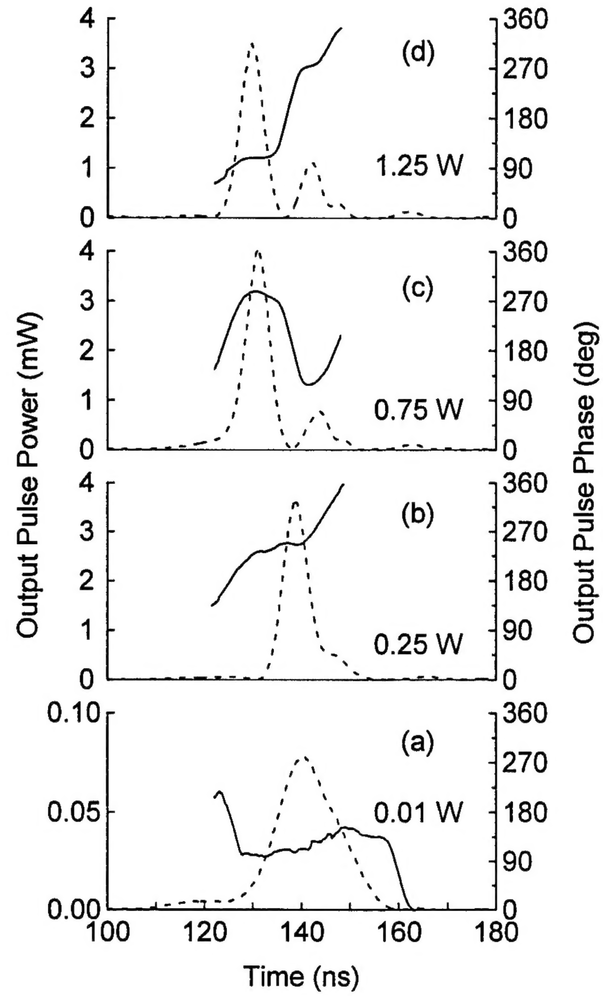

Fig. 5. Experimental phase and power profiles for an MSBVW pulse signal as a function of the input power (Nash *et al.*, 1998).

Figure 5 shows one important result from the phase profile measurements on MSBVW solitons. The dashed curves show the usual power profiles vs. time at the output transducer and the solid lines show the phase across the pulse. If the carrier signal inside the pulse envelope maintains a perfect harmonic form, the phase change is zero. When dispersion is acting to broaden the pulse or nonlinear effects are acting to shift the carrier frequency, the phase profile will be concave upward or concave downward, depending on the nature of the MSW signal. When dispersion and the nonlinear response are compensated, as in the case of a soliton, the phase profile is flat. The flat region of constant phase across the peak region in (b) and (c), and across the main peak and the secondary peak in (d), indicate the formation of solitons.

The discovery of phase profiles as an unambiguous and direct indication of soliton formation has proved to be very useful for soliton device diagnostics. The soliton pulse trains to be considered below, for example, could be instantly verified to consist of solitons simply from phase profile measurements. The phase has also been found to be a critical control parameter for switching and amplification. These effects will also play an important role in the renewal program.

2. Soliton Feedback and Soliton Trains

The use of feedback to control and enhance MME soliton properties was one of the key techniques developed in the current ARO program. The extended use of these techniques has led to decay free soliton trains and a mode locked spontaneous soliton generator. Both effects present important new aspects of soliton physics and also hold profound device implications.

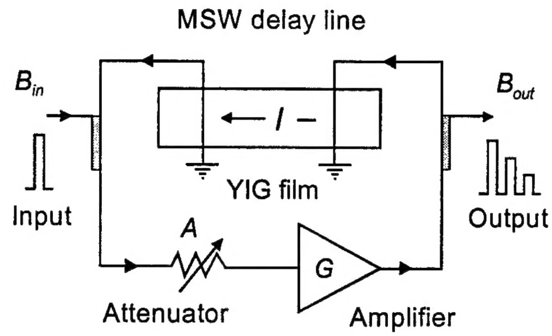

Fig. 6. Schematic diagram of the active magnetostatic wave (MSW) delay line with an attenuator, an amplifier, and a passive MSW YIG film delay line in a feedback loop, and with directional couplers for input and output (Fetisov *et al.*, 1998).

Figure 6 shows a schematic feedback configuration which served as the basis for an "active delay line" (Fetisov *et al.*, 1998). The output pulse train is generated from the single input pulse. As the pulse circulates around the feedback loop, one output pulse is generates for each pass. With simple feedback as shown in Fig. 6, the overall loop gain must be kept fairly low in order to avoid oscillations. Nevertheless, it was possible to achieve pulse decay rates which were significantly smaller than those shown in Fig. 4. The simple feedback scheme in Fig. 6 has not yet been successfully applied to solitons.

Refinements to this scheme have been applied to solitons. The first such application was in the form of an "interrupted" soliton feedback generator (Kalinikos *et al.*, 1997). The circuit was more complicated than in Fig. 6, but the basic change was simply to add a fast microwave switch in series with the attenuator in the feedback loop. This switch was normally closed so that the feedback could work to generate the series of output pulses shown in Fig. 6. It was found, however, that by using the switch to *interrupt* the feedback, one could use this break in the feedback to suppress the oscillations which commence for loop gains of unity or higher. With the input power and other conditions adjusted to produce soliton propagation in the YIG film, the interrupted feedback made it possible to operate the device with a loop gain of unity and produce a very long train of decay free soliton pulses. The maximum time between interruptions which could be used before oscillation set in was about 40 μs.

The second such application was in the form of a mode locked "spontaneous" soliton generator. In this scheme, the switch in the first scheme was used as a modulator and the feedback loop was opened for 10 ns or so once every cycle. If the modulation was synchronized to the loop cycle time for the MSW pulse, it was found that solitons could be generated *spontaneously*. That is, the decay free train of solitons could be produced through mode locking to the modulation and *without any input trigger pulse whatsoever*!

Figure 7(a) shows a representative soliton pulse output train for the mode locked experiment. Even though only nine pulses are shown, the actual train of soliton pulses extends indefinitely. Keep in mind that the gain of the feedback is set at unity and the MSW pulse propagation conditions are set to support solitons in the YIG film. Figure 7(b) shows companion phase profiles for the pulse amplitude profiles in (a). The flat phase regions which straddle the amplitude peaks

provide a direct confirmation that solitons are being generated through this mode locking process. The pulse trains generated through the interrupted scheme are similar to the sequences shown in Fig. 7, except that the interrupted train can only be maintained for a maximum of 40 μs or so.

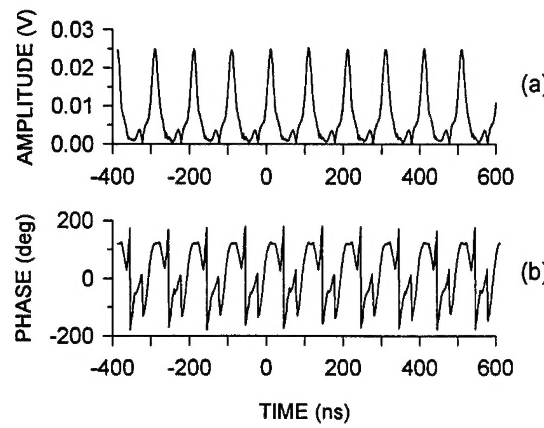

Fig. 7. Graphs (a) and (b) show detected microwave voltage and phase for spontaneously generated MSBVW solitons in the mode locked modulated feedback scheme (Kalinikos *et al.*, 1998).

3. Parametric Amplification of Solitons

The feedback techniques presented above provide one way to maintain the soliton pulse amplitude over many pulse cycles and for long, electronically tunable delay times. A second way to eliminate the problem of soliton decay is to develop some means of direct amplification of the propagating MSW pulse signals. A new parametric technique to accomplish such amplification has been developed.

Figure 8 shows the design of the three transducer microstrip structure used to parametrically pump MME pulses signals. This structure is similar to the structure in Fig. 1, except for the additional center element. This element consists of a microstrip line coupled to a microstrip resonator element positioned midway between the input and output transducers. The pump pulse signal consists of a microwave pulse at approximately twice the carrier frequency of the input MME pulse signal. This pulse is timed to occur just as the signal pulse passes over the resonator element. Parametric coupling between the microwave signal from the resonator to the propagating magnetostatic wave pulse leads to a boost in the amplitude of the signal pulse.

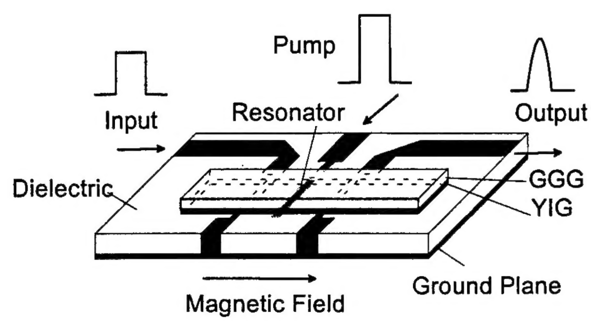

Fig. 8. Three element microstrip structure for the parametric pumping of MME pulse signals. The center element is a microstrip resonator tuned to approximately twice the signal carrier frequency (Kolodin *et al.*, 1998).

Some representative results on pulse amplification for both high and low power input pulses are shown in Fig. 9. Graph (a) is for a high 40-45 mW peak power input pulse power sufficient to produce solitons at the resonator position. The dashed line pulse shape close to 200 ns on the time axis shows the signal level for the propagating MME soliton pulse at the resonator. The solid and dashed pulse shapes at 400 ns show the output signal with and without the parametric pump applied. The gain in the soliton peak power at the output is about 7 dB.

Graph (b) is for a much lower input pulse power of 3.5-4 mW. Here the MSW pulse amplitude at the resonator position is broader, and represents a linear MSW pulse. In this case, the output signals show a much higher gain on the order of 20 dB. Much higher gains are possible for linear MME pulses than for solitons. Solitons cannot be boosted to arbitrarily large amplitudes

because of the self-limiting nature of the nonlinear eigenmode which represents the soliton. This limitation is not present for the linear signals. Details of the technique and additional results, as well as remarks on the theory behind the parametric pumping process may be found in the March 2, 1998 issue of Physical Review Letters (Kolodin *et al.*, 1998).

The above results on decay free soliton trains and the *in situ* amplification of soliton pulses represent an important breakthrough. Up to now, the large decay rate of these MSW pulse signals, even for single crystal YIG films, has been a severe limitation for microwave device applications. This problem has now been eliminated.

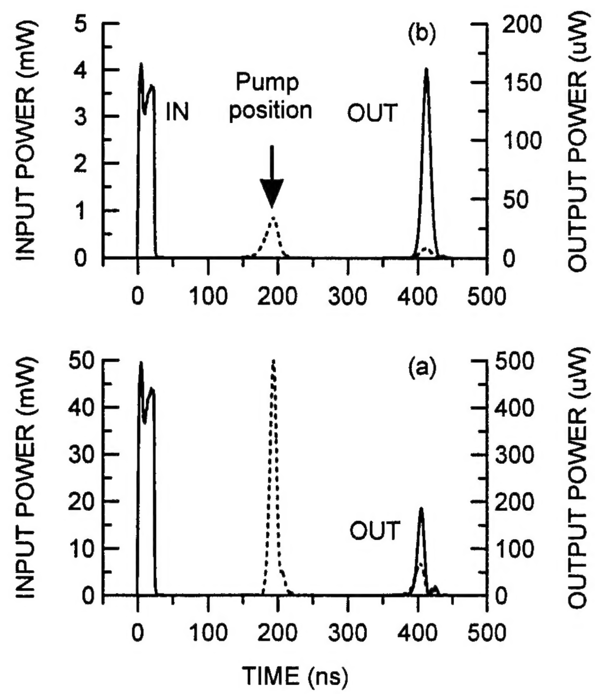

Fig. 9. Representative pulse data with and without parametric pumping. The signal frequency was 4.01 GHz and the pump frequency was 8.05 GHz. Diagram (a) is for a relatively high input pulse power and soliton pulse propagation in the YIG. Diagram (b) is for a lower power input pulse and linear MSW pulse propagation in the YIG (Kolodin *et al.*, 1998).

4. Brillouin Light Scattering on Solitons

One of the objectives of the original MME soliton program was to observe Brillouin light scattering (BLS) on such signals. This objective has now been realized. The original interest in this experiment came from fundamental considerations of the Fourier make-up of the MME pulse. The BLS technique could access this make-up directly and provide direct information on the basic nature of the nonlinear eigenmode which gives rise to soliton properties. From the developments described above, there are additional reason to apply BLS techniques to MME solitons. The scattering gives signals at the frequencies of all the magnetic excitations which are produced or supported in the YIG film. This means that the BLS technique can provide a direct map of the parametric interactions which serve to amplify the spin wave pulses.

The basic BLS setup is shown in Fig. 10. The small element in the magnet gap represents the YIG film with input and output transducers, etc. Scattering can take place between incident photons and the in-plane wave vector magnons. Scattered photons are up shifted or down shifted by the magnon frequency and BLS spectra yield information on the wave vector distribution for the spin waves or magnetostatic waves in the film.

For the study of MME solitons, the sample in Fig. 10 is replaced by a YIG film transducer structure as shown schematically in Fig. 11. The laser light is used in a forward scattering configuration. A magnon of wave vector k_m produces scattered light at wave vector k_s as shown. The signal for this k_m value is selected by the pinhole/diaphragm and analyzed by the Fabry Perot. Details and background on the BLS technique for the analysis of magnetic excitations and MSW signals is described in recent papers by Kabos *et al.* (1996).

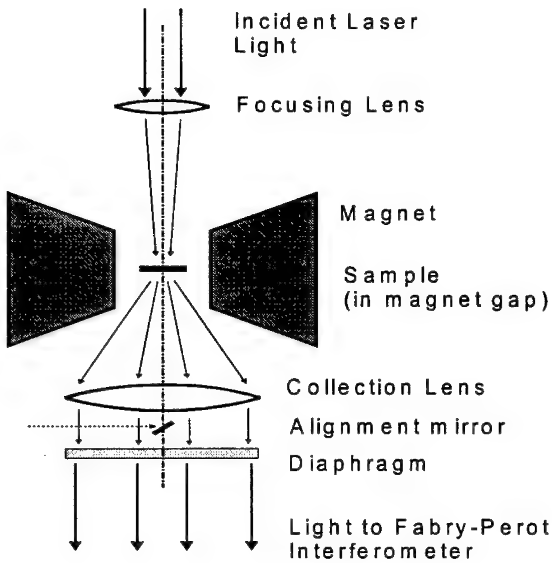

Fig. 10. Schematic Brillouin light scattering setup for thin films (after Kabos *et al.*, 1996).

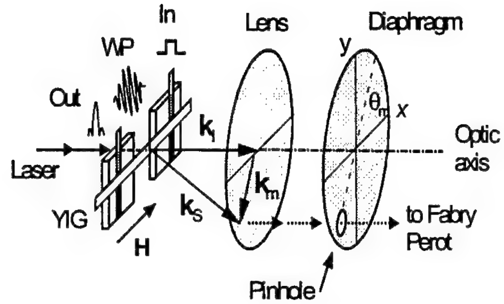

Fig. 11. Schematic of YIG film transducer structure and optical configuration for wave vector selective Brillouin light scattering experiments (Xia *et al.*, 1998).

Figure 12 shows one representative result from the recent BLS measurements on MME solitons. The diaphragm symbols indicate the pinhole or slit arrangement needed to obtain the data. The main point for this proposal is that (1) the main signal corresponds to low wave numbers which match more-or-less the soliton wave number range, and (2) there is an additional magnon signal at high wave numbers, as shown in inset (b). The recent Phys. Rev. Letter by Xia *et. al.* (1998) presents data on magnon angle and wave number distributions for solitons. The BLS technique provides a powerful way to analyze nonlinear MSW signals. As discussed in the renewal proposal, Brillouin light scattering is expected to be an important tool for soliton device analysis.

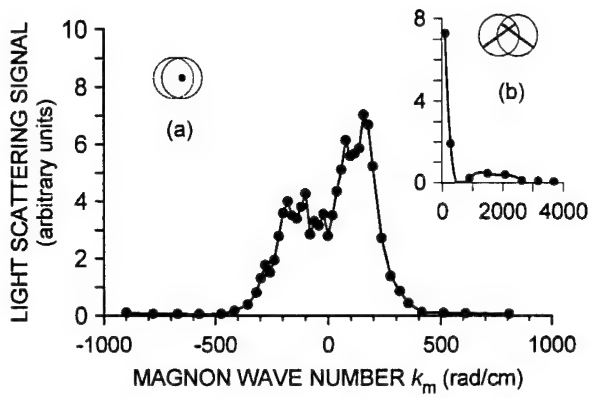

Fig. 12. Soliton light scattering signal as a function of the magnon wave number k_m. Graph (a) is for a 200 μm pinhole aperture and a wave vector parallel to the soliton propagation direction. Graph (b) is for a double slit arrangement to select out both k_m and different propagation directions. The data are for a direction at about 40° to the soliton propagation direction. (Xia *et al.*, 1998).

5. Soliton Order, Thresholds, and Velocity

The soliton pulses shown in Fig. 3 change from a single peak in graph (a) to a double peaked and a triple peaked shape in (b) and (c). These changes provide one indication of different soliton

orders. Even though there is not always a one-to-one correspondence between the number of peaks and soliton order, higher input powers do produce higher order solitons. These changes in soliton order have associated changes in soliton properties which may be used to advantage for microwave signal processing. The use of different order optical solitons for the coding of high data rate pulse signals in fiber optic cables is an area of intense research. The properties of higher order microwave solitons present similar opportunities for microwave signal processing.

Figures 13 and 14 show the two main effects which have been discovered under the present program. The soliton number parameter n in Fig. 13 corresponds to the highest order soliton for a given threshold power at a given input pulse width. Note the indication of an initial soliton state at $n = 1$, a clear leveling off at a plateau corresponding to $n = 2$, and the trend toward another plateau at $n = 3$. Full results are given by Nash *et al.* (1995). The main point here is that one may devise relatively simple procedures to determine the order for MME solitons.

The Fig. 13 results concern power thresholds for different order solitons. The data in Fig. 14 are for a much more direct effect, the change in soliton velocity with power. These changes in velocity correlate directly with predictions based on soliton threshold powers and modulational instability. While the theory for MME solitons, based on inverse scattering and the nonlinear Schrödinger equation, does not predict any change in soliton velocity with power, the results of Xia *et. al.* (1998) clearly show that the velocity of MME solitons is power dependent and probably related to soliton order.

6. Soliton Devices - Switching and Bistability

Figure 15 shows the concept for a cw or a pulse microwave switch based on soliton self-focusing. At low power, the microwave power into PORT 1 generates an MSW signal in the YIG which propagates, spreads somewhat, and illuminates the antennas for both PORT 2 and PORT 3. At higher powers, solitons are formed. The self-focusing associated with the soliton propagation can cause the YIG signal to selectively excite only the PORT 2 antenna. Of course, changes in the direction of the static magnetic field, antenna configurations, etc., may be used to

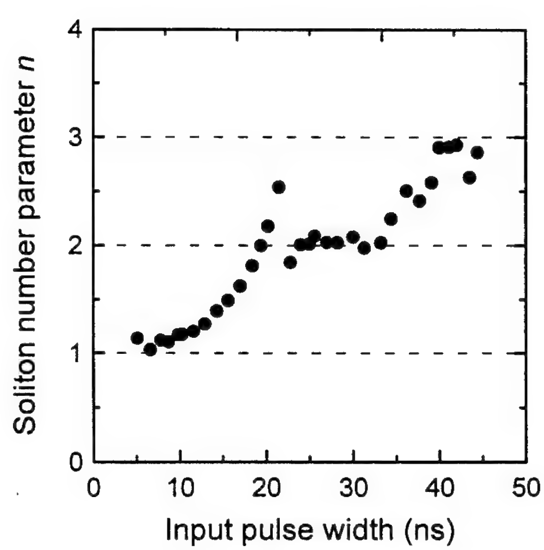

Fig. 13. Experimental soliton number parameter n versus input pulse width (Nash *et al.*, 1995).

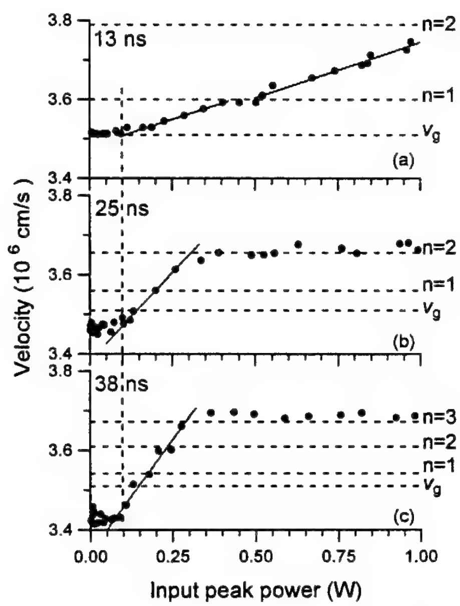

Fig. 14. Soliton velocity as a function of power (Xia *et al.*, 1998).

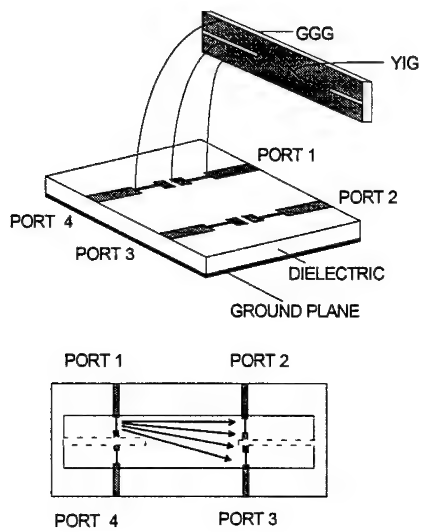

Fig. 15. Schematic soliton self focusing switch device.

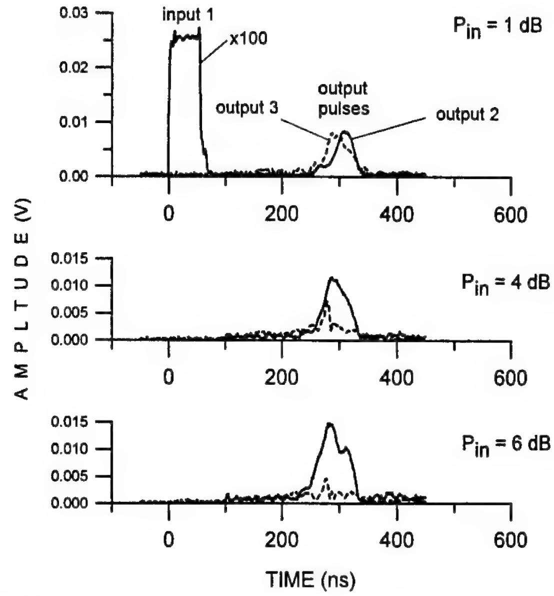

Fig. 16. Pulse data for the soliton self focusing switch (P. A. Kolodin, unpublished, 1998).

change to one or the other output port at low power and the alternate port at high power, etc. Microwave power directed to a port other than PORT 1 could be routed to other ports as well.

Figure 16 shows some actual data for the setup in Fig. 15 with the input signal to PORT 1 and monitored outputs for PORT 2 and PORT 3. The top graph shows the input pulse and the output signals for both output ports at low input power. The two output pulses are approximately the same. As the input power is increased, the signal at PORT 3 is diminished and the signal at PORT 2 remains the same. This power switching effect is due to the self-focusing effect from the MSBVW soliton signal.

As a final example of the types of devices which may be realized in these MSW soliton microstrip experiments, consider an adaption of the three transducer device in Fig. 8. A simplified schematic of the modified structure is shown in Fig. 17. The modification involves the center element, which is changed to a wide resonator. The effect of the wide resonator on the MSBVW signal from input to output is shown in Fig. 18. The sharp notch labeled "operating point" shows the large attenuation which is produced at 4 GHz by the wide resonator. This notch occurs when no microwave power is applied to the resonator element. When a double frequency pump signal is applied to the resonator, the parametric amplification produces a boost in the output rather than attenuation.

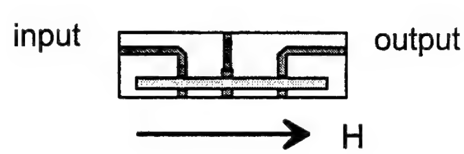

Fig. 17. Wide resonator three transducer structure.

The effect of the resonator on the MSBVW signal at the output is shown in Fig. 19. The figure shows a wide input pulse and the output pulse which results with no resonator power and with resonator power. Without resonator power, the output is essentially zero as shown by the noisy baseline trace. With resonator power, one finds a sizeable output pulse. These results show that the wide resonator under powered down and powered up conditions produces an off-on microwave switch.

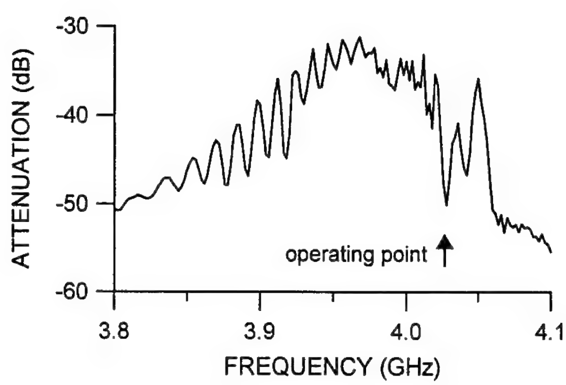

Fig. 18. MSBVW frequency response with a wide microstrip resonator as the central passive element in the structure of Fig. 8 (P. A. Kolodin, unpublished, 1998).

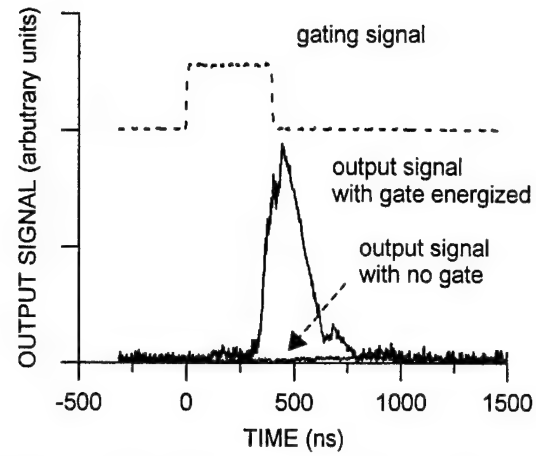

Fig. 19. Pulse data for the soliton self-focusing switch (P. A. Kolodin, unpublished, 1998).

This wide resonator switch is also phase sensitive. If the phase of the parametric pump signal applied to the resonator is changed relative to the phase of the input signal, one can vary the output signal over a wide range. This effect is shown in Fig. 20. The phase between the signal and the double frequency pump was controlled by using a frequency doubler to derive the parametric pump from the signal.

Finally, Fig. 21 shows an output power vs. input power bistable response characteristic which has been recently obtained through the use of magnetic field feedback for a magnetostatic surface wave (MSSW) delay line. The idea behind this device is to (1) use the MSW structure as one arm

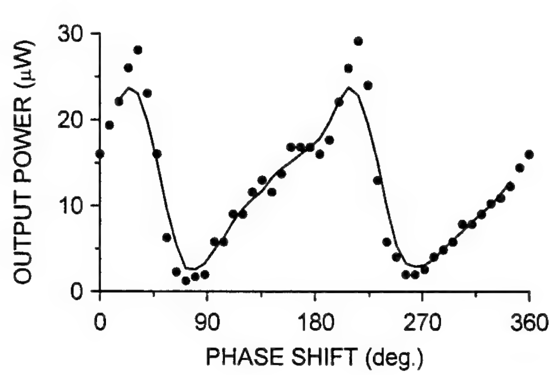

Fig. 20. Output signal with resonator power applied as a function of relative phase between signal and resonator power (P. A. Kolodin, unpublished, 1998).

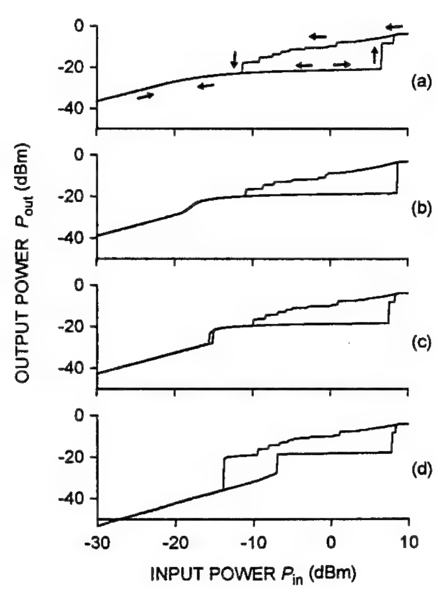

Fig. 21. Typical bistable power response for an magnetostatic surface wave interferometer with magnetic field feedback (Y. K. Fetisov, unpublished, 1998).

of a microwave interferometer and (2) use the interferometer output to generate a feedback shift in the magnetic field bias which determines the interferometer characteristic. The result consists of bistable response curves of the sort shown in Fig. 21. Bistability is an important device concept in fiber optics. It is possible that the kind of effects shown in Fig. 21 could be used in a similar way for microwave devices and systems.

7. Soliton Devices - Oscillators and Delay

The sequence of pulses shown in Fig. 7 demonstrates the judicious use of feedback to produce decay free trains of soliton pulses. The data in Fig. 7 are for spontaneously generated solitons produced by modulated feedback and mode locking. The modulation was synchronized to the single pass loop cycle time for the pulse. The main contribution to this cycle time is the delay time of the MSW soliton pulse from input to output for the YIG film transducer structure. This means that the time spacing between the output pulses shown in Fig. 7 can be controlled by changing the magnetic field.

In the case of interrupted feedback (Kalinikos *et al.*, 1997), one starts with an input pulse at a selected carrier frequency. The magnetic field, pulse width, and carrier frequency are set to support soliton formation and propagation from input to output in the YIG structure. The gain of the feedback is set to unity. In this arrangement, the single input microwave pulse would (i) produce an initial soliton and (ii) this soliton would circulate around the feedback loop and produce a series of narrow, dispersion free, and decay free output pulses, *except* for the fact that the unity gain leads to parasitic oscillations which completely destroy the integrity of the train. This problem was solved by *interrupting* the feedback every four hundred cycles or so.

The interrupted feedback arrangement for the production of a long sequence of narrow, dispersion free, and decay free pulses is shown in Fig. 22. The schematic shows more detail than the diagram in Fig. 6, but the main point of emphasis is the element in the feedback loop labeled SWITCH #1. This switch is used to interrupt the feedback loop every 40 μs or so. For a typical single loop delay time of 100 ns, this corresponds to an interruption every 400 pulse cycles. A cumulative delay time of 40 μs without pulse degradation of decay would be a very desirable feature for electronically tunable delay lines. Here, the single pass delay time is electronically tunable through control of the input pulse carrier frequency or the static magnetic field.

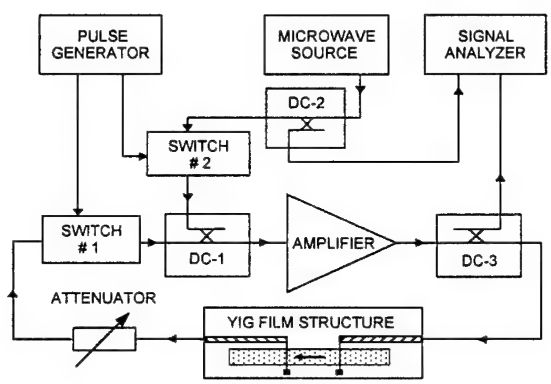

Fig. 22. Diagram of YIG film soliton pulse train generator interrupted feedback arrangement (Kalinikos *et al.*, 1997).

Figure 23 shows the pulse timing. The three diagrams show the expected sequences of soliton pulses which are produced when the gain G of the feedback loop is less than unity, equal to unity, and greater than unity, respectively. Without the momentary switching off of the feedback between sequences, as indicated by the gaps between the "#1 ON" regions, one would only have oscillations for the middle and right diagrams and no pulse trains at all.

Figure 24 shows the kinds of pulse trains which can be realized experimentally. Graph (b) is the most important. This sequence of output pulses was obtained for a loop gain of unity, and

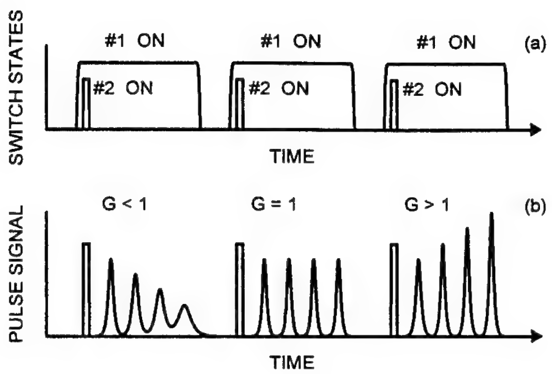

Fig. 23. Schematic illustration of (a) the switch timing pulses for the feedback control switch # 1 and the input pulse control switch #2 and (b) output pulse sequences for three different limiting cases for the total feedback gain G, as indicated (Kalinikos *et al.*, 1997).

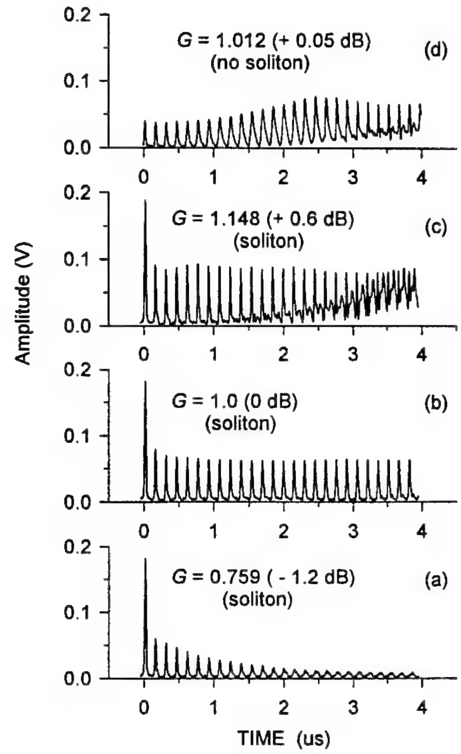

Fig. 24. Four sequences of soliton train pulses for different values of the loop gain, as indicated. The trains were produced from single rectangular input pulses 25 ns in width applied to the coupler input DC-2 in Fig. 24. For (a), (b), and (c), the input power was high enough to produce solitons. For (d), the input power was reduced below the level needed to produce solitons. (Kalinikos *et al.*, 1997).

the output train is decay free and dispersion free. Such timed pulses could prove to be very useful for microwave signal processing and delay line applications.

Graphs (a), (c), and (d) show the effect of different gains and lower power levels on the output train. When the gain is below unity, as in (a), the pulse train just dies out. The drop in amplitude also results in a transition from soliton to linear dispersion prone pulse propagation in the YIG and the observed spreading in the pulses as well. In (c), with the gain above unity, one does not find a continued growth in pulse amplitude as indicated in Fig. 23 for $G > 1$. This is because of the self limiting property of solitons. One cannot simply take a given soliton pulse and increase the amplitude without limit. Solitons of a given order, order one in this case, can be supported only over a narrow range of amplitudes or input pulse widths. This is the origin of the multiple peak profiles which are formed for large pulse widths in Fig. 3 and at high power in Fig. 5, as well as the phase plateaus shown in Fig. 5.

8. Soliton Devices - Power Limiting

Power limiters provide a crucial function in basic microwave transmit-receive systems and in radar countermeasure devices and systems. The data previously presented in Fig. 5 shows that MME solitons possess microwave limiting properties. Note that the dashed line amplitude profiles in graphs (b), (c), and (d) remain at about 4 mW, even though the input power is increased five-fold. The microwave device configurations developed so far for microwave solitons in thin YIG

films have not involved limiting. In the next phase of the program, we plan to investigate MME soliton limiting processes and possible device applications.

The basic soliton limiter action is demonstrated by the output peak power P_{out} versus the input peak power P_{in} response which is observed for MME solitons. Some typical data for 13 ns MME pulses and an operating point frequencies of 4.8-5.0 GHz are shown in Fig. 25. The response starts out as linear, increases to a more rapid nonlinear response as an order one soliton is formed. Above about 200-400 mW of input power, depending on the frequency, the response peaks out and appears to gradually decrease. The peak and the fall off at higher powers are due to the formation of multiple peaks in the pulse output and corresponding higher order solitons.

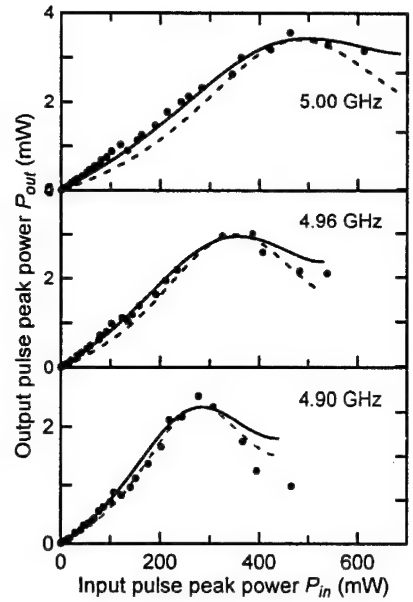

Fig. 25. Typical response curves of output pulse peak power P_{out} vs. input pulse peak power P_{in} for MSBVW MME pulses. The propagation distance was 4 mm, the YIG film thickness was 10.2 μm, the external applied magnetic field was 1187 Oe, and the input pulse width was 13 ns. The solid and dashed curves show the results of calculations with and without magnetostatic band edge filtering (H. Y. Zhang *et al.*, 1998).

C. List of Publications and Presentations

1. Archival Publications and References for Section B: (in year/page number order)

* Indicates that reprint has been filed with AMXRO-ICA-L
# Indicates that reprint filing with AMXRO-ICA-L is pending.

(1)* "Theory of magnetostatic waves for in-plane magnetized anisotropic films," M. J. Hurben and C. E. Patton, J. Magn. Magn. Mat. **163**, 39-69 (1996).

(2)* "Magnetostatic wave dynamic magnetization response in yttrium iron garnet films," M. A. Tsankov, M. Chen, and C. E. Patton, J. Appl. Phys. **79**, 1595-1603 (1996).

(3)* "Bistable microwave oscillator with magnetostatic wave signal-to-noise enhancer in the feedback loop," Y. K. Fetisov, P. Kabos, and C. E. Patton, Elec. Lett. **32**, 1894-1895 (1996).

(4)* "Butterfly curves and critical modes for second order spin wave instability processes in yttrium iron garnet films," P. Kabos, C. E. Patton, G. Wiese, A. D. Sullins, E. S. Wright, and L. Chen, J. Appl. Phys. **80**, 3962-3971 (1996).

(5)* "Formation, propagation, reflection, and collision of microwave envelope solitons in yttrium iron garnet films," N. G. Kovshikov, B. A. Kalinikos, C. E. Patton, E. S. Wright, and J. M. Nash, Phys. Rev. **B54**, 15210-15223 (1996),

(6)* "Observation of the amplification of spin-wave envelope solitons in ferromagnetic films by parallel magnetic pumping," B. A. Kalinikos, N. G. Kovshikov, M. P. Kostylev, P. Kabos, and C. E. Patton, Pis'ma Zh. Éksp. Teor. Fiz. **66**, 346-350 (1997) [JETP Lett. **66**, 371-375 (1997)].

(7)* "Decay free microwave magnetic envelope soliton pulse trains in yttrium iron garnet thin films," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Phys. Rev. Lett. **78**, 2827-2830 (1997).

(8)* "High-resolution Brillouin light scattering and angle-dependent 9.4 GHz ferromagnetic resonance in MBE-grown Fe/Cr/Fe on GaAs," S. M. Rezende, M. A. Lucena, F. M. de Aguiar, A. Azevedo, C. Chesman, P. Kabos, and C. E. Patton, Phys, Rev. **B55**, 8071-8074 (1997).

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(10)* "Decay properties of microwave magnetic envelope solitons in yttrium iron garnet films," H. Xia, P. Kabos, C. E. Patton, and H. E. Ensle, Phys. Rev. **B55**, 15018-15025 (1997).

(11)* "Active magnetostatic wave delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, IEEE Trans. Magnetics **34**, 259-270 (1998).

(12)# "Brillouin light scattering and magnon wave vector distributions for microwave magnetic envelope solitons in yttrium iron garnet thin films," H. Xia, P. Kabos, H. Y. Zhang, P. Kolodin, and C. E. Patton, Phys. Rev. Lett. **81**, 449-452 (1998).

(13)* "Amplification of microwave magnetic envelope solitons in thin yttrium iron garnet films by parallel pumping," P. A. Kolodin, P. Kabos, C. E. Patton, B. A. Kalinikos, N. G. Kovshikov, and M. P. Kostylev, Phys. Rev. Lett. **80**, 1972-1975 (1998).

(14)# "Calculation of the formation time for microwave magnetic envelope solitons," R. A. Staudinger, P. Kabos, H. Xia, B. T. Faber, and C. E. Patton, IEEE Trans. Magnetics **34**, 2334-2338 (1998).

(15)* "Phase profiles of microwave magnetic envelope solitons," J. M. Nash, P. Kabos, R. Staudinger, and C. E. Patton, J. Appl. Phys. **83**, 2689-2699 (1998).

(16)# "On the velocity characteristics of microwave magnetic envelope solitons," H. Xia, P. Kabos, R. A. Staudinger, and C. E. Patton, Phys. Rev. **B58**, 2708-2715 (1998).

(17)# "The modeling of microwave magnetic envelope solitons in thin ferrite films through the nonlinear Schrödinger equation," H. Y. Zhang, P. Kabos, H. Xia, R. A. Staudinger, P. A. Kolodin, and C. E. Patton, J. Appl. Phys.**84**, 3776-3785 (1998).

(18)* "Self-generation of microwave magnetic envelope soliton trains in yttrium iron garnet thin films," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Phys. Rev. Lett. **80**, 4301-4304 (1998).

(19)* "Theory of two magnon scattering microwave relaxation and ferromagnetic resonance linewidth in magnetic thin films," M. J. Hurben and C. E. Patton, J. Appl. Phys. **83**, 4344-4365 (1998).

(20)# "Microwave magnetic envelope solitons in thin ferrite films," C. E. Patton, P. Kabos, H. Xia, P. A. Kolodin, H. Y. Zhang, R. Staudinger, B. A. Kalinikos, and N. G. Kovshikov, J. Mag. Soc. Japan, in press (1998).

(21)# "Microwave bistability in a magnetostatic wave interferometer with external feedback," Y. K. Fetisov and C. E. Patton, IEEE Trans. Magnetics, submitted (1998).

2. Other Related Publications (no reprints filed):

(1). "Observation of the amplification of spin-wave envelope solitons in ferromagnetic films by parallel magnetic pumping," B. A. Kalinikos, N. G. Kovshikov, M. P. Kostylev, P. Kabos, and C. E. Patton, Pis'ma Zh. Éksp. Teor. Fiz. **66**, 346-350 (1997) [JETP Lett. **66**, 371-375 (1997)].

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(3). "Angle dependence of the ferromagnetic resonance linewidth in easy-axis and easy-plane single crystal hexagonal ferrite disks," M. J. Hurben, D. R. Franklin, and C. E. Patton, J. Appl. Phys. **81**, 7458-7467 (1997).

(4) "Observation of self-generation of dark envelope solitons for spin waves in ferromagnetic films," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, Pis'ma Zh. Eksp. Teor. Fiz. **68**, 229-233 (1998) [JETP Lett. **68**, 243-247 (198)].

3. Conference Abstracts (no reprints filed):

(1) "Ferrite thin film microwave and millimeter wave soliton physics and devices," NATO ARW Workshop - Nonlinear Microwave Signal Processing: Towards a New range of Devices - Nonlinear Microwave Magnetic and Magneto-optic Information Processing, Rome, Italy, October 5, 1995.

(2) "Phase properties of microwave magnetic envelope dark solitons in yttrium iron garnet thin films," J. M. Nash, P. Kabos, C. E. Patton, and R. Staudinger, Abstract Book, 40th Annual Conference on Magnetism and Magnetic Materials, Philadelphia, Pennsylvania, November 6-9, 1995.

(3) "Experimental determination of microwave magnetic envelope soliton phase profiles," J. M. Nash, P. Kabos, and C. E. Patton, 1996 Intermag Conference, Seattle, Washington, April 9-12, 1996.

(4) "Magnetostatic wave pulses and solitons in an active delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, 1996 Intermag Conference, Seattle, Washington, April 9-12, 1996.

(5) "Active magnetostatic wave delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, International Magnetics Conference, Seattle, Washington, April 9-12, 1996.

(6) "Experimental determination of microwave magnetic envelope soliton phase profiles," J. M. Nash, P. Kabos, and C. E. Patton, International Magnetics Conference, Seattle, Washington, April 9-12, 1996.

(7) "Active magnetostatic wave soliton delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, International Conference on Millimeter and Submillimeter Waves and Applications III, SPIE International Symposium on Optical Science, Engineering, and Instrumentation, Denver, Colorado, August 6, 1996.

(8) "Magnetostatic wave pulses and solitons in an active delay line," Y. K. Fetisov, P. Kabos, and C. E. Patton, Union Radio-Scientifique Internationale (URSI) Conference, Lille, France, August 28 - September 5, 1996.

(9) "On the width vs. peak amplitude response for microwave magnetic envelope solitons in yttrium iron garnet films," B. A. Kalinikos, N. G. Kovshikov, C. E. Patton, and J. M. Nash, The 7th International Conference on Ferrites, Bordeaux, France, September 3-6, 1996.

(10) "Formation and damping of magnetostatic backward volume wave envelope solitons in yttrium iron garnet films," Y. K. Fetisov, H. E. Ensle, P. Kabos, H. Xia, B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton The 7th International Conference on Ferrites, Bordeaux, France, September 3-6, 1996.

(11) "Microwave magnetic solitons and devices in ferrite thin films," C. E. Patton, M. Chen, M. A. Tsankov, J. M. Nash, P. Kabos, B. A. Kalinikos, N. G. Kovshikov, H. Hua, and Y. K. Fetisov, NATO Advanced Research Workshop on Microwave Physics and Techniques, Sozopol, Bulgaria, September 30 - October 5, 1996.

(12) "Sources of microwave loss in pulsed laser deposited ferrite thin films," C. E. Patton and H. J. Hurben, NATO Advanced Research Workshop on Microwave Physics and Techniques, Sozopol, Bulgaria, September 30 - October 5, 1996.

(13) "Propagation properties of microwave magnetic envelope solitons in thin yttrium iron garnet films at 5 GHz," H. Xia, P. Kabos, C. E. Patton, and H. E. Ensle, 41st Annual Conference on Magnetism and Magnetic Materials, Atlanta, Georgia, November 12-15, 1996.

(14) "Multiple scale derivation of the nonlinear Schrödinger equation for solitons in magnetic thin films," S. E. Mock, M. J. Ablowitz, and C. E. Patton, 41st Annual Conference on Magnetism and Magnetic Materials, Atlanta, Georgia, November 12-15, 1996.

(15) "The Landau-Lifshitz equation - precessing magnets," C. E. Patton, Special Pre-conference Symposium on High Speed Switching, International Magnetics Conference, New Orleans, Louisiana, March 31, 1997.

(16) "Microwave magnetic envelope soliton train generator," B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, International Magnetics Conference, New Orleans, Louisiana, April 1-4, 1997.

(17) "Precision velocity measurements on microwave magnetic envelope solitons in thin films," H. Xia, P. Kabos, C. E. Patton, and A. N. Slavin, International Magnetics Conference, New Orleans, Louisiana, April 1-4, 1997.

(18) "Calculation of the formation time for microwave magnetic envelope solitons," R. A. Staudinger, P. Kabos, H. Xia, B. T. Faber, and C. E. Patton, International Magnetics Conference, New Orleans, Louisiana, April 1-4, 1997.
(19) "Ferrite thin films - problems and possibilities for microwave devices," C. E. Patton, Defense Advanced Research Projects Agency Workshop on Frequency Agile Materials for Electronics, Washington, DC, May 15, 1997.
(20) "Microwave magnetic envelope solitons in thin films, soliton physics and devices," C. E. Patton, Ferrite Measurement Workshop, Microwave Theory and Techniques Symposium, Denver, Colorado, June 9, 1997.
(21) "Microwave bistability in a magnetostatic surface wave interferometer with external magnetic field feedback," Y. K. Fetisov and C. E. Patton, The 7th Joint MMM-Intermag Conference, San Francisco, California, January 6-9, 1998.
(22) "Amplification of microwave magnetic envelope solitons in yttrium iron garnet thin films by parallel pumping," P. A. Kolodin, P. Kabos, and C. E. Patton, The 7th Joint MMM-Intermag Conference, San Francisco, California, January 6-9, 1998.
(23) "Brillouin light scattering on microwave magnetic envelope solitons in yttrium iron garnet films at 5 GHz," H. Xia, P. Kabos, H. Y. Zhang, P. A. Kolodin, and C. E. Patton, The 7th Joint MMM-Intermag Conference, San Francisco, California, January 6-9, 1998.
(24) "Velocities of microwave magnetic envelope solitons in thin films," C. E. Zaspel, P. Kabos, C. E. Patton, H. Xia, and H. Y. Zhang, The 7th Joint MMM-Intermag Conference, San Francisco, California, January 6-9, 1998.

4. Other Presentations by Principal Investigator (no reprints filed):

(1) "Microwave and millimeter wave losses in ferrite films," Naval Research Laboratory, Washington, DC, February 14, 1996.
(2) "Solitons, fact and fancy," Sigma Xi Lecture, Colorado State University, Fort Collins, Colorado, March 29, 1996.
(3) "Studies of magnetic excitations by Brillouin light scattering," University of Kaiserslautern, Germany, June 7, 1996.
(4) "Microwave envelope solitons in magnetic thin films," Laboratoire de Magnetisme et d'Optique de Versailles, Versailles, France, June 12, 1996.
(5) "A Tutorial on high frequency envelope solitons," Technical Hochschule Darmstadt, Darmstadt, Germany, June 21, 1996.
(6) "High frequency magnetic excitations, resonance, spin waves, and solitons," Department of Physics, University of Colorado, Boulder, January 15, 1997.
(7) "Microwave solitons in magnetic thin films - soliton numbers, soliton energies, soliton velocities, and soliton trains," Department of Applied Mathematics, University of Colorado, Boulder, January 30, 1997.
(8) "The Landau-Lifshitz equation and damping in magnetic systems," Department of Physics, Montana State University, Bozeman, April 10, 1997.
(9) "Microwave solitons in magnetic thin films - soliton numbers, soliton energies, soliton velocities, and soliton trains," Department of Physics, Montana State University, April 11, 1997.
(10) "Solitons - fact and fancy," Department of Physics, University of North Dakota, Grand Forks, December 4, 1997.

(11) "High frequency magnetic excitations, resonance, spin waves, and solitons," University of North Dakota, Grand Forks, December 5, 1997.

(12) "Microwave solitons in magnetic films - soliton numbers, soliton energies, soliton velocities, and soliton trains," Department of Physics, Colorado State University, Ft. Collins, December 8, 1997.

(13) "Microwave magnetic solitons in magnetic thin films," Institute of Physics, Academy of Sciences of the Czech Republic, May 14, 1998.

(14) "Physics of microwave magnetic envelope solitons - phase, soliton numbers, amplitude and energy decay, power dependent velocities, and soliton modeling," International Symposium on Spin Waves, A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia, May 20, 1998.

(15) "Brillouin light scattering and magnon wave vector distributions for microwave magnetic envelope solitons in magnetic thin films," International Symposium on Spin Waves, A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia, May 20, 1998.

(16) "Two magnon scattering relaxation processes in anisotropic ferrite films," International Symposium on Spin Waves, A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia, May 20, 1998.

D. List of Participating Scientific Personnel

1. Senior Personnel:

Dr. Carl E. Patton	Principal Investigator
Dr. Pavel Kabos	Research Professor (now at National Institute of Standards and Technology)
Dr. Yuri Fetisov	Visiting Scientist (Moscow Institute of Radio Engineering, Electronics, and Automation, Moscow, Russia)
Dr. Boris Kalinikos	Visiting Scientist (St. Petersburg Electrotechnical University, Russia)
Dr. Pavel Kolodin	Visiting Scientist (now at P & H Laboratories, Simi Valley, California)
Dr. Nikolai Kovshikov	Visiting Scientist (St. Petersburg Electrotechnical University, Russia)
Dr. Michael Wittenauer	Visiting Scientist

2. Postdoctoral and Graduate Student Personnel:

Dr. Hua Xia	Postdoctoral Research Fellow (now at the Department of Physics, Ohio State University)
Dr. Hong Yan Zhang	Postdoctoral Research Fellow (now in the Department of Chemistry, Colorado State University)
Dr. Michael J. Hurben	Graduate Student and Ph.D. Candidate; Ph.D., 1996; Postdoctoral Research Fellow (now at Seagate Recording Heads, Bloomington, Minnesota)

Dr. Jon M. Nash	Graduate Student and Ph.D. Candidate; Ph.D., 1996; Postdoctoral Research Fellow (now at Montemorelos University, Montemorelos, Nuevo Leon, Mexico)
Mr. Richard G. Cox	Graduate Student and Ph.D. Candidate
Mr. Mark M. Scott	Graduate Student
Mr. Alex Nazarov	Graduate Student
Mr. Scott E. Mock	Graduate Student (Applied Mathematics, University of Colorado, Professor Mark Ablowitz, advisor)
Mr. Byron Faber	Graduate Student; M. S., 1997 (now at Tektronics, Inc., Beaverton, Oregon)
Mr. Harold Ensle	Graduate Student
Mr. Reinhold Staudinger	Exchange Student from Germany (Fachhochschule Regensburg - Practical training, now at Derby Associates, Fort Collins, Colorado)
Mr. Stephan Kestl	Exchange Student from Germany (Fachhochschule Regensburg - Practical training)
Mr. Josef Aebner	Exchange Student from Germany (Fachhochschule Regensburg - Practical training)

3. Undergraduate and High School Student Personnel:

Mr. Eric Wright	Physics Major and Merit Work Study Student; B.S., 1995 (now a graduate student in the Department of Applied Mathematics, University of Colorado, Boulder)
Mr. Allan Sullins	Physics Major and Merit Work Study Student; B.S., 1995 (now an electrical contractor, Steamboat Springs, Colorado)
Mr. Matthew Bigelow	Undergraduate Student (Physics); B. S., 1998 (now at the University of Rochester Optics Institute, Rochester, New York)
Mr. Mark Fassler	Undergraduate Student (Physics)
Mr. Richard Miller	Undergraduate Student (Physics)
Mr. Timothy Bigelow	High School Student (REAP Program); Undergraduate Student (Electrical Engineering)
Mr. Rajesh Oad	High School Student (REAP Program, now an undergraduate student in mechanical engineering)
Mr. Nathan Ickes	High School Student (REAP Program, now an undergraduate student in physics at MIT)
Mr. Robert Viola	High School Student (REAP Program, now an undergraduate student in mechanical engineering)
Mr. Jonathan Hurst	High School Student (REAP Program, now an undergraduate student in mechanical engineering at Carnegie Mellon University)
Mr. Troy Wieck	High School Student (REAP Program, now an undergraduate student in electrical engineering at the University of Colorado)

Mr. Richard McMurtry	High School Student (REAP Program, now an undergraduate student at Brigham Young University)
Mr. Matthew Iyer	High School Student (REAP Program, currently a Fort Collins High School senior)

REPORT OF INVENTIONS

Magnetostatic Wave Microwave Soliton Feedback Generator
Nikolai G. Kovshikov, Boris A. Kalinikos, Carl E. Patton
(Invention Disclosure April 19, 1996)

Magnetostatic Wave Microwave Soliton Parametric Amplifier
Pavel A. Kolodin, Pavel Kabos, Carl E. Patton
(Invention Disclosure June 17, 1997, Provisional Patent Application, filed September 17, 1997, granted January 26, 1998)

Magnetostatic Wave Frequency Selective Phase Locked Parametric Switch
Pavel A. Kolodin, Pavel Kabos, Carl E. Patton
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